# Net Radiative Forcing from Widespread Deployment of Photovoltaics

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If photovoltaics (PV) are to contribute significantly to stabilizing the climate, they will need to be deployed on the scale of multiple terawatts. Installation of that much PV would cover substantial portions of the Earth's surface with dark-colored, sunlight-absorbing panels, reducing the Earth's albedo. How much radiative forcing would result from this change in land use? How does this amount compare to the radiative forcing *avoided* by substituting PV for fossil fuels? This analysis uses a series of simple equations to compare the two effects and finds that substitution dominates; the avoided radiative forcing due to substitution of PV for fossil fuels is approximately 30 times larger than the forcing due to albedo modification. Sensitivity analysis, including discounting of future costs and benefits, identifies unfavorable yet plausible configurations in which the albedo effect substantially reduces the climatic benefits of PV. The value of PV as a climate mitigation option depends on how it is deployed, not just how much it is deployed—efficiency of PV systems and the carbon intensity of the substituted energy are particularly important.

## Introduction

Photovoltaics (PV) provide an attractive way to meet growing world energy demand because they produce electricity without emitting greenhouse gases (GhGs). Systems are becoming less expensive, installations are growing quickly, and the potential available resource remains abundant (*1*). But PV can only help to stabilize the climate if it makes a meaningful contribution to world energy supply and displaces carbon-intensive forms of energy production. To do that, multiple terawatts (TW) of PV will need to be deployed.

Both history and prospective models show that adverse societal effects can emerge from apparently beneficial technologies when they are deployed at a very large scale (*2*−*6*). In this vein, other studies have looked at the possible impacts of widespread PV, including the use of toxic chemicals in the PV production process (*7*), the availability of raw materials (*8*), and the extent to which PV is a net producer of energy over its lifecycle (*9, 10*). An additional concern, which has been expressed but not rigorously evaluated, is that covering a large portion of the Earth's land area with light-absorbing solar panels will reduce the albedo of the Earth's surface, thereby increasing radiative forcing and ultimately having a positive effect on global surface temperatures (*11*−*15*). This study weighs the merits of this concern.

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Two scenarios of PV deployment over this century were used to estimate (Figure 1) the radiative forcing associated with reducing the Earth's albedo and (2) the negative forcing resulting from substitution of PV for fossil fuel electricity generation (1). Sensitivity analysis, identification of areas for improvement, and assessment of the differential temporal patterns of impacts follow the description of the net radiative forcing effect.

**Radiative Forcing due to PV Albedo Effect.** In this section the effect of widespread use of PV on the Earth's albedo and the extent of the resulting radiative forcing are estimated.

**Amount of PV Installed.** To address this highly uncertain factor, two scenarios were constructed. The first, "IPCC median" draws on results of an analysis of the assumptions on technology deployment used by the IPCC in its Special Report on Emissions Scenarios (SRES) (*16*) and Third Assessment Report (TAR) (*17*). For this meta-scenario, the median value of PV deployment across these 34 emissions scenarios is used. At this median level for 2100, PV would supply 6% of world energy use. For the second scenario, a "high-diffusion" path is constructed, which represents a likely upper bound on PV diffusion in 2100. The IPCC scenarios described above are used to produce an estimate of world energy demand in 2100. The assumption defining the high-diffusion scenarios is that PV accounts for 50% of world energy consumption in 2100 (see the Supporting Information).

So far, these two scenarios describe levels in 2100. The literature on technology diffusion provides a means with which to describe a path over time. Dating back to the middle of the last century (*18*), a wide array of empirical case studies have found that new technologies tend to diffuse into widespread use according to a logistic function (*19, 20*). Cumulative diffusion follows this functional form because the population of early adopters, intermediate adopters, and laggards is normally distributed (*21*). Adoption of technology tends to be slow early on when reliability is unproven and only early adopters risk using the new device. Diffusion accelerates as initial problems are worked out and complementary innovations enable widespread adoption. Finally, diffusion slows as substitutes emerge and the market reaches saturation. This function for the diffusion of technologies takes the following form:

$$Q_t = \frac{Q_{\max}}{1 + e^{-(a+b(t-t_0))}} + k \qquad (1)$$

where $Q_t$ is the PV energy production in exajoules at time, $t$; $a$ is the constant of integration used to position the curve horizontally on the time scale; $b$ is the rate of growth coefficient; $k$ is the amount of PV installed at time, $t_o = 0$; and $Q_{\max}$ is the difference between the saturation level and $k$ (see the Supporting Information for values of coefficients used).

Two logistic curves are fitted to historical data, as well as the points in the scenarios described above, to create a PV diffusion curve (Figure 2). The lower line shows the amount of PV energy using the median of the IPCC scenarios and the

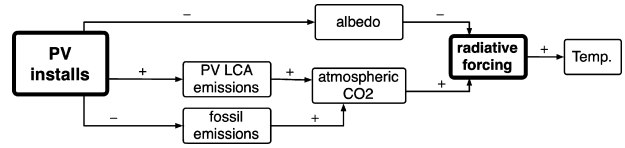


**FIGURE 1. Influences on radiative forcing from PV installations. Signs (+ and −) represent direction of relationship.**

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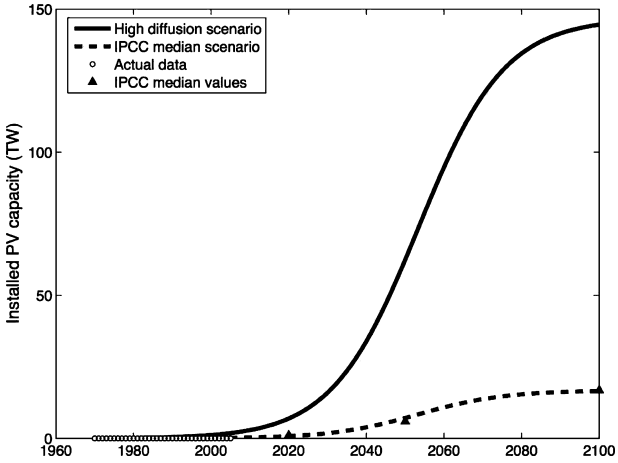


**FIGURE 2. Technology diffusion curves for PV. Logistic function based on median values across emissions scenarios used by IPCC (lower) and scenario in which PV accounts for half of world energy supply in 2100 (upper).**

upper line shows PV energy in the high-diffusion scenario, in which PV supplies 50% of world energy consumption in 2100.

**Land Area Covered by PV.** The area of the earth's surface covered by PV panels, $A_t$ is related to the energy produced by PV ($Q_t$) in exajoules, electrical efficiency of the panels ($\eta_t$), and average incoming solar radiation ($I_s$), according to the following:

$$A_t = \frac{Q_t}{\eta_t I_s} \tag{2}$$

A time series for the electrical conversion efficiency of PV panels is created using historic trends (*22*), industry targets (*23*), and theoretical physical limits such that $\eta_{2100} = 0.28$. The level of incoming solar radiation ($I_s$) used is 183 W/m$^2$, which is the annual average incoming solar radiation for seven selected cities (see the Supporting Information for detail).

The diffusion function in eq 1 is combined with eq 2 to calculate the land area covered by PV panels. In the first scenario, using the mean of the IPCC scenarios, PV covers 0.07 million km$^2$ in 2100, 0.05% of global land area. The land area covered in 2100 under the high-diffusion scenario is 0.58 million km$^2$, 0.39% of land area. As a comparison, this value is approximately equal to the land area currently devoted to major roads in the U.S.

**Radiative Forcing from Albedo Change.** Photovoltaics use antireflective coatings and textured surfaces to maximize the incoming solar radiation absorbed by the cell, such that the 30% albedo (reflectivity) value for raw silicon can be reduced to 1% in laboratory settings (*24*). Poor siting and orientations can make real-world albedo values as high as 10% (*25*). The albedo of solar cells ($\alpha_{pv}$) used in this analysis is 5%.

Although the overwhelming majority of PV systems to date have been installed on rooftops, the increasing use of energy services and urbanization of the world's population expected over this century imply that the density of energy consumption (in W/m$^2$) will exceed that of incoming solar radiation once it has been converted into electricity; the area of rooftops will be insufficient to produce large portions of energy supply. As a result, the estimates used are that 20% of the PV is installed on rooftops, 40% on grasslands, and 40% in deserts. These three types of land cover are represented using the index, $i = 1$ to 3. These proportions are applied to the total land area covered by PV from above, to calculate the area covered in each type of landscape ($A_{i,t}$). The following surface albedo values are used (*26, 27*):

$$\alpha_{rooftop} = 0.10,\ \alpha_{grassland} = 0.20,\ \alpha_{desert} = 0.33.$$

The change in radiative forcing due to albedo modification is calculated for each year and land cover type multiplying incoming solar radiation by the change in albedo values. Because about a quarter of the reflected short-wave radiation ($\rho = 0.23$) is absorbed by the atmosphere on its way out from the earth's surface, the factor $1 - \rho$ is added, which offsets some of the change in surface forcing (*28*). Local radiative forcing ($L$) due to the albedo change for each land cover type is calculated using

$$L_{i,t} = I_s(\alpha_i - \alpha_{pv})(1 - \rho) \tag{3}$$

See the Supporting Information for an explanation of this equation.

The global effect of PV radiative forcing ($F$) is calculated at each time, $t$ by multiplying the local effect, $L_c$ by the area of PV installations and then dividing by the area of the surface of the earth, 510 million km$^2$, $A_e$. This radiative forcing is calculated for each year and summed across each land cover type using

$$F_t = \sum_{i=1}^{3} \frac{L_t A_{i,t}}{A_e} \tag{4}$$

Using, the high-diffusion scenario for PV, the change in radiative forcing is 0.0293 W/m$^2$ in 2100. Compare this ~0.03 W/m$^2$ level to the radiative forcing caused by anthropogenic GhG emissions since preindustrial times of 2.6 W/m$^2$, and to the albedo effect of previous land use change of −0.2 W/m$^2$ (*28*). The radiative forcing in the IPCC median scenario is 0.0033 W/m$^2$.

**Radiative Forcing from Substitution of PV for Fossil Fuels.** From a climate change perspective, the benefit of PV is that it can substitute for carbon-intensive energy supply. Here, the total emissions of carbon avoided in each of the PV diffusion scenarios are calculated.

The world energy system today emits GhGs with a carbon intensity of 17.1 tons of carbon/TJ (*29*). This value for carbon intensity, $G_t$ is used for all periods because it is close to the upper bound of possible scenarios for 2100 (*30*) making it consistent with our simulation of replacing PV for carbon intensive energy supply. It is also consistent with recent trends (*31*). Replacing less carbon intensive energy supply is examined later in a sensitivity analysis.

Lifecycle analyses of PV emissions show that manufacturing, use, and disposal of PV devices produces GhG emissions at the rate of approximately 15−35 g$CO_2$ eq/kWh of PV electricity for current systems. While even higher rates are possible in particularly adverse locations with poor solar insolation and carbon intensive power supply this rate is likely to fall to below 10 g as input energy becomes decarbonized (*32*). This analysis uses a midpoint estimate for lifecycle factor ($\phi$) of 20 g for the IPCC median scenario and 10 g for the high-diffusion scenario, because widespread diffusion of PV in the latter case will make energy input for manufacturing less carbon intensive. The lifecycle carbon emissions (LCA) from PV are $LCA_t = \phi E_t$. These values result in a lifecycle "loss" in emissions reductions for 2100 of 9.7 and 4.6% of emissions reductions for the IPCC median and high diffusion scenarios, respectively.

The annual carbon emissions offset by PV ($c_t$) is calculated by multiplying energy produced ($E_t$) by carbon intensity ($G_t$) and subtracting the lifecycle emissions for PV.

$$c_t = E_t G_t - LCA_t \tag{5}$$

Emissions reductions in 2100 are 1.6, and 15.1 GT C/year for the two scenarios. The net emissions substituted can be integrated from the initial deployment of PV until the end

**TABLE 1. Summary of Results for 2100**

| | IPCC median | high diffusion | units |
|---|---|---|---|
| PV energy | 104 | 926 | EJ |
| area of PV | 0.07 | 0.58 | $10^6$ km$^2$ |
| $RF_{albedo}$ | 0.003 | 0.029 | W/m$^2$ |
| LCA effect | 9.7% | 4.6% | |
| C avoided | 78 | 727 | $10^{15}$ g |
| C avoided | 18 | 168 | $ppm_v$ |
| $RF_{CO_2}$ | −0.102 | −1.031 | W/m$^2$ |
| $RF_{net}$ | −0.099 | −1.002 | W/m$^2$ |
| $RF_{ratio}$ | −30.8 | −35.2 | |

of the century to calculate total carbon emissions offset by PV ($C$). PV offsets 727 GT of carbon emissions over the entire time period in the high diffusion scenario and 78 GT C in the IPCC median scenario.

Next, the radiative forcing attributable to these avoided emissions is calculated. First the change in atmospheric concentrations of $CO_2$ from these avoided carbon emissions, $C$ is calculated. Using that half of the emissions will be absorbed by oceans and terrestrial ecosystems over the century, $\gamma = 0.5$ and the relationship for converting a stock of carbon to parts per million $\varepsilon = 2.16$ GT/ppm $_v$, the change in atmospheric concentration due to the PV offset is calculated using $P_{pv} = \gamma C/\varepsilon$.

The change in atmospheric concentrations is converted to radiative forcing using

$$\Delta R = \sigma \ln\left(\frac{P}{P_o}\right) \tag{6}$$

where $\sigma$ is radiative forcing from doubling $CO_2$ concentrations, 5.35; $P$ is the new level of atmospheric $CO_2$; and $P_o$ is the original level of $CO_2$ (see the Supporting Information). To estimate the avoided radiative forcing due to PV (S) we compare radiative forcing in 2100 for the case with PV and without PV.

$$S = \sigma \ln\left(\frac{P_{\mathrm{BAU}} - P_{\mathrm{PV}}}{P_{\mathrm{o}}}\right) - \sigma \ln\left(\frac{P_{\mathrm{BAU}}}{P_{\mathrm{o}}}\right) \tag{7}$$

For $P_o$ current atmospheric concentration, 385 ppm is used and for the business as usual case in 2100, $P_{\mathrm{BAU}}$ 960 ppm is used, which is the value in Scenario A1F1, the fossil intensive scenario which serves as a baseline against which PV would be deployed. The use of the fossil intensive scenario is consistent with our BAU carbon intensity assumption of the present value, 17tC/TJ. It is also consistent with recent trends in carbon intensity (*31*). The calculated values of $P_{\mathrm{PV}}$ for the IPCC median and high-diffusion scenarios are 18.1 and 168.3 ppm, respectively. Radiative forcing from substituting PV for other sources of energy supply are −0.102 and −1.03 W/m$^2$ for the two scenarios.

**Net Radiative Forcing.** Radiative forcing provides a useful basis for comparing the effects of a diverse set of factors perturbing the Earth's energy balance on globally averaged temperature change (*28*)—particularly for $CO_2$ and land albedo change (*33*). A comparison of the two radiative forcing effects in 2100 shows that the fossil fuel substitution effect is a factor of 35 times larger than the albedo effect in the high diffusion case and 31 times larger in the IPCC median case (see Table 1). Putting these figures in historical perspective, forcing from land use change from preindustrial to present is about five times larger than expected forcing from PV albedo change (*28*). While a unit of forcing from albedo modification and a unit of forcing from increases in $CO_2$ concentrations each exert equivalent effects on a globally averaged temperature basis, the Supporting Information describes how differences in the mechanisms by which they affect the earth's energy budget may differ in their local impacts, temporal scales, and indirect effects.

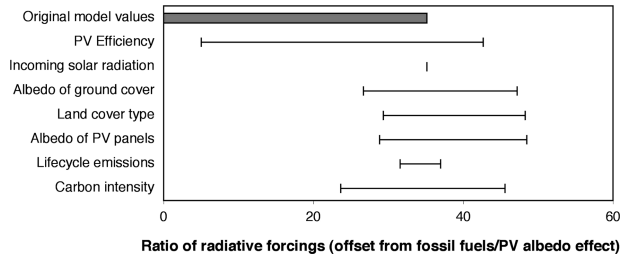


**FIGURE 3. Sensitivity of radiative forcing ratio to uncertainty in parameters.**

**Sensitivity Analysis.** Next, uncertainty in the model parameters is estimated and the sensitivity of the ratio between the two radiative forcings to this uncertainty is assessed. Figure 3 shows that, for the values evaluated, the range of the fossil fuel offset to albedo ratio around the original value for the high-diffusion scenario of 35.2 is 5.0−48.5. Uncertainty in the main parameters is estimated as follows.

**PV System Efficiency.** The energy conversion efficiency of PV modules is assumed to increase to 28% by 2100, about double current commercial average levels. It is plausible, possibly through the widespread use of concentrators, that the average efficiency of commercial cells could reach 35%. Another scenario considered is that in which efficiency levels decrease because very inexpensive to manufacture PV becomes available, such as purely organic PV. We consider a scenario in which efficiencies only reach 5% in 2100.

**Incoming Solar Radiation.** The model uses an $I_s$ based on the average observed for seven large metropolitan areas worldwide, 183 W/m$^2$. Here, the impacts of assuming all the PV is installed in areas with incoming solar radiation similar to that of the sunniest metropolitan area (231 W/m$^2$) and then for the least sunny area (129 W/m$^2$) are assessed. Note that the results are insensitive to the incoming solar radiation at the location of installation; in areas with poor insolation, where more land area is required, the lower intensity of reflected radiation exactly offsets the added absorption due to larger land area requirements.

**Albedo of Ground Cover.** The model uses albedo values for ground cover of $\alpha_{\mathrm{rooftop}} = 0.10$, $\alpha_{\mathrm{grassland}} = 0.20$, $\alpha_{\mathrm{desert}} = 0.33$. The sensitivity analysis uses values 25% higher and lower than the original values.

**Ground Cover Type.** The model assumes 20% of PV is installed on rooftops, 40% in agricultural areas, or "grasslands", and 40% in deserts. If roof space is less of a constraint than originally imagined, one could assume that 50% is installed on rooftops, and the remainder split between croplands and deserts. At the other end of the range, it is plausible that land use and energy density constraints in populated areas mean that 60% is installed in deserts, 10% on roofs, and 30% in grasslands.

**Albedo of PV Panels.** The model assumes that PV systems reflect 5% of incoming solar radiation, $\alpha_{pv} = 5\%$. It was noted above that laboratory albedo values can be as low as 1% and that those in poorly sited field installations can be as high as 10%. The impact on radiative forcing of assuming all PV is installed at the laboratory best, and then assuming all is installed like the poorly sited systems is evaluated.

**Lifecycle Emissions.** The model assumes that energy is consumed in the manufacturing, use, and disposal of PV devices at the rate of 10 g of $CO_2$ per kWh of PV electricity produced. Two additional cases are assessed: one in which energy consumption remains at the rate currently observed in the worst cases, 30 g$CO_2$ /kWh, and one in which energy

used for PV comes from a completely carbon free energy supply, 0 $gCO_2$ /kWh.

**Carbon Intensity.** The model assumes that the carbon intensity (tC/TJ) of the world energy system remains at its historical level. It is conceivable, for example through the exploitation of abundant coal and unconventional petroleum resources, that the carbon intensity of the world energy system in 2100 will be higher than it is today. A scenario is included where carbon intensity is 25% higher than today. Alternatively, one could imagine decarbonization occurring at its historical rate, as the energy system is increasingly made up of renewables and other low-carbon technologies.

**Simultaneous Effects.** When the uncertainty in each parameter is assessed individually, the sensitivity analysis supports the robustness of the claim in this paper that the albedo effect is not substantial relative to that of fossil fuel substitution. The size of the substitution effect is never less than 5 times as large as the albedo effect (Figure 3).

But is it possible that the albedo effect might still be a concern if some of these uncertainties arrive in adverse combinations? For example, one internally consistent scenario is that the levels of each of the uncertain parameters turn out to be at the least favorable end of their ranges: electrical conversion efficiencies are low; module reflectance values are low; systems are installed above surfaces that are highly reflective; and the power production which PV substitutes for includes large amounts of renewables, nuclear, or other low-carbon sources of energy production. High lifecycle energy use is not included in this scenario since it is inconsistent with the assumption of large amounts of low carbon energy sources. One might imagine the development of very low cost PV material that is inherently inefficient and designed to be highly absorptive of solar radiation. The low energy density of such a low efficiency material would make it more appropriate in sparsely populated desert locations than on roofs. The substitution of PV for less carbon intensive energy supply is feasible in a situation in which PV substitutes for the highest marginal cost alternative, which is likely to be a mix of natural gas and other renewables. Even in this extremely unfavorable scenario, the fossil fuel offset effect on radiative forcing is still 1.9 times as large as the albedo effect, and PV remains an effective climate change mitigation option.

**Time Value of Radiative Forcing Effects.** As an additional sensitivity analysis, the time value of the radiative forcing costs and benefits of incremental PV deployment is calculated. Whereas the previous analysis looked at the ratio of radiative forcing impacts at two points in time, 2050 and 2100, this looks at the lifecycle radiative forcing impacts through 2200 for an incremental PV system installed in mid-21st century. Discounting is import because the time profile of the costs and benefits are different: the radiative forcing costs of albedo change are instant and last only as long as the panels are installed. In contrast, the radiative forcing benefits of fossil fuel substitution accumulate over time and persist for the atmospheric lifetime of $CO_2$.

A first step is to assign a value to the various effects of PV on the climate. Almost all existing and proposed efforts to price climate change externalities are based on mass of emissions of $CO_2$ and equivalents, such as $/t$CO_2$. The analysis in this paper shows how this is insufficient because the change to the earth's albedo affects radiative forcing directly, without affecting emissions; prices based on emissions unfairly preference direct radiative forcing impacts. A new pricing methodology, that incorporates radiative forcing directly, is required to provide incentives to reduce these effects. Payment for environmental damages could be set in annual values of $W/m^2$, or more explicitly, ($W \cdot year/m^2 \cdot year$), which can be converted into values of, for example, $TWh/m^2$ of radiative forcing. The social value of the damages resulting from radiative forcing is denoted as $\pi$. While an actual value is not necessary to calculate the radiative forcing effects, this value is likely on the order of $\$10^{10}$ per $W/m^2$ when applied globally.

Next, the time value of net radiative forcing effect of an incremental PV installation is estimated using the levels over time of deployment, emissions offset, $CO_2$ concentrations, albedo effects, and radiative forcings, as calculated in the sections above (see the Supporting Information). To assess the time value of a system lifetime, $\ell_{pv}$ of 30 years, and an assumed atmospheric lifetime of CO2, $\ell_{CO_2}$ of 100 years, the value is calculated for 130 years. The initial social discount rate used is $\delta$ is 2%. Radiative forcing from the albedo effect of PV installations is $\chi$ and that from emissions offset net of lifecycle accounting is $\upsilon$. The discounted value of the each of these effects, $F_{alb}$, and $F_{CO_2}$ is the sum of the present value of the product of radiative forcing and the social value of the damages, $\pi$:

$$F_{alb} = \sum_{t=0}^{\ell_{pv}} \pi \chi_t (1+\delta)^{-t} \tag{8}$$

$$F_{CO_2} = \sum_{t=0}^{\ell_{pv}+\ell_{CO_2}} \pi \upsilon_t (1+\delta)^{-t} \tag{9}$$

These equations allow calculations of the effect of discounting on the ratio of the two effects, $F_{CO_2}/F_{alb}$. Note that in these ratios, the parameter $\pi$ cancels out so the value of $\pi$ does not affect the ratio. Whereas the nondiscounted value for the ratio is 62, the value discounted at 2% is 30. Similarly, considering the most unfavorable case from the sensitivity analysis, for which the ratio is 4.0, the discounted ratio is 2.0. With a discount rate of 5% the base case ratio is 16 and the ratio in the unfavorable case is 1.1.

Even in the most unfavorable case, deploying PV still provides net benefits to the climate. But consideration of the time value of the benefits and costs of an incremental PV installation over its lifecycle increases the importance of the albedo effect. In this unfavorable case, with a 2% social discount rate, half of the climate change benefits are lost to the albedo effect. This result suggests caution about *how* large scale deployment of PV is pursued. To that end, it also implies that pricing climatic damages in terms of radiative forcing, rather than simply in mass of emissions, may be necessary to weigh the full costs and benefits of technologies, such as PV, with potentially important climatic impacts.

**Improving the Effectiveness of PV for Climate Stabilization.** The sensitivity analysis shows that PV remains an attractive climate change mitigation option even when the albedo effect reaches its maximum value within the range of uncertainty assessed in this chapter. Yet the uncertainties discussed above are not purely exogenous; they can be influenced by the actions of governments, installers, manufacturers, and households. As a result, a second implication of this sensitivity analysis is that it points to future technical improvements in PV design and configuration that can enhance the value of PV as a tool for climate change mitigation. Table 2 shows the effects on radiative forcing of five important improvements in PV system design and implementation. For example, row 2 of Table 2 indicates that changes in the design of PV modules that increase the light reflected from 5% of incoming solar radiation to 10%—such as coatings that selectively reflect wavelengths below the semiconductor material's bandgap—would improve PV's climate mitigation performance by 0.8%.

**Module Design.** *Improving Module Efficiency.* Studies that focus on reducing PV's cost per unit of electricity produced sometimes claim that we should be indifferent between a set of technical improvements that halves the cost of producing

**TABLE 2. Effect of Technical Improvements on Radiative Forcing from PV**

| improvement | original value | improved value | $\delta$ radiative forcing ($W/m^2$) | % $\delta$ radiative forcing effect |
|---|---|---|---|---|
| PV efficiency | 13% | 28% | −0.04 | 4.1% |
| PV reflectance | 5% | 10% | −0.01 | 0.8% |
| land cover ($\alpha$) | 20% roofs | 40% roofs | −0.01 | 0.5% |
| lifecycle energy | 10 g | 0 g | −0.05 | 5.3% |
| energy substituted | natural gas | coal | −1.67 | 96.3% |

PV material and one that doubles the efficiency of modules. Both create the same benefit in terms of reducing cost per unit of electrical output. But this analysis suggests that improving efficiency can have benefits beyond reducing cost. All things being equal, a doubling of efficiency will halve the land area covered by PV panels thus halving the radiative forcing from PV's effect on the Earth's albedo.

*Increasing reflectance.* PV modules are typically covered with coatings and surface textures that maximize the amount of light absorbed by the cell. However, it is feasible, that surfaces could be designed so that they more selectively reflect wavelengths that are unlikely to be converted into electricity by the semiconductor material used in the cell.

**Land Cover Type.** Installing dark-colored PV panels on top of the land or structures with lowest reflectance values minimizes the albedo effect. For example, installations above low-albedo roofs or parking surfaces are preferable to those on high-albedo surfaces such as deserts.

**Lifecycle Energy Use.** The use of energy in the manufacturing and disposal of PV devices offsets fossil fuel emissions reductions on the order of 5−10%. Two ways these losses can be avoided are by reducing energy consumption during the manufacturing and disposal processes and by using low carbon energy sources. The effectiveness of the second method depends on the availability of low carbon energy supply other than PV, since using PV energy to manufacture PV will simply reduce the availability of carbon free PV energy to other sectors of the economy.

**Substituted Energy Production.** This study shows that the fossil fuel substitution effect is much larger than the albedo effect. PV maximizes its value as a climate change mitigation tool when it displaces the most-carbon intensive types of energy production. At one extreme, PV that displaces coal—the most carbon-intensive energy source—can have a large effect on reducing radiative forcing from carbon emissions. At the other, PV that displaces zero-carbon energy production, such as other renewables or nuclear power, displaces no emissions; in that case, the albedo effect would make its net contribution to radiative forcing positive. The difference between substituting for gas and for coal, shown in Table 2 shows how important the type of energy displaced is to total radiative forcing avoided.

**Targeting Improvements in PV beyond Cost Reductions.** For the most part, efforts to improve the viability of photovoltaics have sought to find ways to reduce the cost of PV systems per unit of electricity generated (*23, 34*). Cost reductions are certainly critical to the widespread deployment of PV. But cost per energy produced is really an inverse proxy for PV's climate-related value, rather than a precise metric because cost does not comprehensively capture its usefulness as a tool for mitigating climate change. In addition to its benefits, PV has small adverse effects on climate stability. In particular, the carbon intensity of the energy production being displaced by PV is by far the most important factor affecting the net radiative forcing from PV.

The other technical changes shown in Table 2 also have substantial, albeit smaller, beneficial effects on climate. In addition, they have the advantage of perhaps requiring more modest changes to the energy system as a whole.

This study has found that the climatic benefits resulting from substitution of PV for fossil fuels far outweigh the unfavorable effects due to the change in the Earth's albedo. Still, by pursuing a path of technology development and deployment that minimizes the albedo effects of widespread deployment of PV, its value as a tool for climate change mitigation can be enhanced. The discounting exercise shows that decisions about incremental installations need to consider the time path over which the costs and benefits of radiative forcing effects occur. As a result, pricing climatic damages in terms of $W/m^2$ of radiative forcing, not just in tons of $CO_2$ emissions, may be necessary to provide incentives to avoid a situation resembling the unfavorable scenario described above. In addition to correcting incentives, long-term monitoring of the directions of technical progress, the characteristics of installation sites, and the carbon intensity of the energy sources being displaced is important if we are to take full advantage of the potential of PV as a climate change mitigation option.

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## Supporting Information Available

Details of the methodology and values used. This material is available free of charge via the Internet at http://pubs.acs.org.

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